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Integrating Electric Vehicles into the German Electricity Grid – an Interdisciplinary Analysis

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Abstract

This study analyses the integration of electric vehicles (EV) into the German power grid including different demand side management (DSM) approaches from a technical, economical and user perspective. For this an overview of the future German electricity market with the focus on EV integration is given. It is shown that for conservative EV penetration rates the effect on the electricity generation is marginal while the shortage in the regional and local electricity grid could be already significant. DSM in combination with smart grids can help to tackle this issue by controlled charging of EVs. One simple concept is to postpone the charging process by offering incentives to vehicle users e. g. with dynamic electricity tariffs. The common Time-of-Use (TOU) tariff defines in advance a dynamic tariff scheme according to the load forecast for the following days. This allows to release the local electricity grid and to increase the share of renewable energies: In times of high electricity generation by renewable energies and low electricity demand the price is low and vice versa. The impact of these dynamic tariffs on the charging process of EVs is shown in a techno-economic analysis for an exemplary urban high voltage grid by an optimising energy model. These strong impacts are however somewhat reduced by the acceptance and the low profits for the single user. At least for the users in a German field trial, environmental aspects played a major role in influencing the charging behaviour – this gives still hope for the future.

Keywords: load management, smart grid, incentive, dynamic charging, photovoltaic

1 Introduction

In order to avoid the risks of global warming the world society decided to decrease its greenhouse gas (GHG) emissions and launched the Kyoto Protocol. However, the sector specific development of global GHG emission composition in recent decades shows, that the transport sector with its increasing CO_2 emissions is going to assume a leading role within global GHG emissions. This becomes even more relevant if the rising motorization in developing countries within the next decades is taken into account [1]. A doubling of the global light duty vehicle (LDV) fleet until 2050 is very likely [1]. In developed countries it is often the sole sector that is still increasing its GHG emissions ([2], for the European Union).

One solution for this challenge is seen in the electrification of vehicles, assuming an adequate clean electricity supply. This, however, might increase the already existing pressure to reduce GHG emissions within the electricity market. Especially for the German market the challenges are already complex due to the ambitious targets of cutting CO_2 emissions down to around 40 % until 2020 compared to 1990 (German Integrated Energy and Climate Protection Program [3]), phasing out of nuclear energy until 2022 (AtG, ref. no. 17/6070) and ensuring a minimum share on renewable energy of 80 % until 2050 [4]. This is going to be achieved with a high share of wind generation and hydro, biomass, geothermal and photovoltaic (PV) generation of electricity. Hence, the electricity generation in Germany is becoming increasingly volatile, less controllable and at the same time more decentralized [5].

An increased market penetration of electric vehicles (EV) would raise electricity demand presumably in the evening peak hours [6]. From the current perspective, this development, together with the less controllable electricity generation, requires either (1) grid extensions or / and (2) different demand side management (DSM) approaches to influence the electricity demand and to release grid components especially on lower grid levels [7].

The paper is focusing on the integration of battery electric vehicles (BEV) into the German electricity system and is structured as follows. After a short introduction into the German electricity sector the impact on the power grid by EV is shown. Possible answers, focusing on DSM, are given in chapter 4. Chapter 5 gives an impact analysis of EV on an urban high voltage grid with uncontrolled and controlled charging. The following chapter deals with the current status of research concerning the acceptance of controlled charging of EV as part of DSM. This leads to the concluding statement whether controlled charging can help to overcome some challenges within the German electricity grid.

2 The German Electricity System

The European unbundling process to breakup the monopoly situation within the electricity market in separating electricity generation from grid operation is largely transposed in the German energy system. There are several dozen market participants, but the domi nance of four utilities is still apparent: The big four hold still the lion's share of the large-scale power plants, are partly still affiliated with their transmission grid operators (TSO) and contain own sales departments. On the distribution grid level, which is still the metier of municipal utilities, the market is not completely unbundled, too.

The electricity grid is usually divided in different voltage levels due to Ohmic resistance decreases quadratically with higher voltage. The transmission grid, 380 kV, is responsible for the national balancing of electricity and serves as feeding point for most conventional power plants and large wind power plants. The distribution grid on 110 kV and 10 or 20 kV level distributes electricity within a given region and delivers electricity to industrial consumers. The low voltage grid (usually 0.4 kV) gives access to private households and usual PV systems.

Utilities trade their electricity on different exchange markets (e. g. spot or derivate market) and for ancillary grid services (e. g. frequency regulation) on the reserve markets. The current power plant fleet consist of 23.2 % lignite, 22.4 % nuclear, 18.6 % coal, 13.8 % natural gas, 16.6 % renewable resources, and 5.3 % others. The renewable energy generation consists of 6 % wind, 4.6 % biomass, 3.3 % hydro, 1.9 % PV, and 0.8 % other renewable energy sources [8]. In order to achieve the target of 58 % renewable energy generation in 2050 the share on fossil fuels and nuclear energy has to decline from a share of about 85 % in 2008 to below 20 % in 2050 [9] (cf. Figure 1).

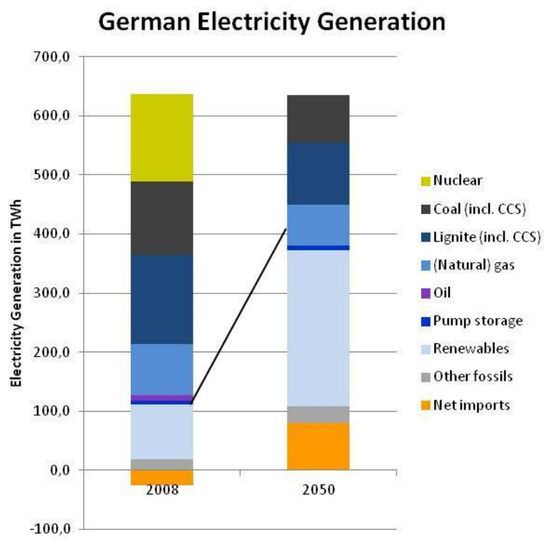

FIGURE 1: Gross electricity generation in Germany for 2008 and 2050 [9]

The impact from EV on electricity generation is in the medium term marginal: The target of the German government of one million EV in 2020

[10] would lead to an additional demand of about 0.5 % of total national electricity demand. The time of demand is however somewhat inappropriate and hence the impact on the power grid might be more significant.

3 Impacts on the power grid by EV

A solely charging process of an EV is far from being crucial for the power grid. However the high simultaneousness of charging processes in one neighbourhood might challenge the local grid components considerably. This is mainly due to the following two reasons:

- the high power compared to usual household load curve (especially for fast charging) and
- the high simultaneousness of arrival timesin the evening hours for home charging.

These challenges are already known from PV systems – however with reciprocal current flows. The usual peak for an average household is not more than 3 kW (cp. Figure 2). A demand of more than 20 kW is very seldom – even though the maximum connection power for a detached house is above 43 kW. An exception is households with electric night-storage heaters, which has a high simultaneousness and a high power demand. However, most installed heaters charge automatically according a control signal from the grid in the evening hours and their decreasing share of about 5 % of installed private heating systems in Germany [11] makes their impact more and more negligible.

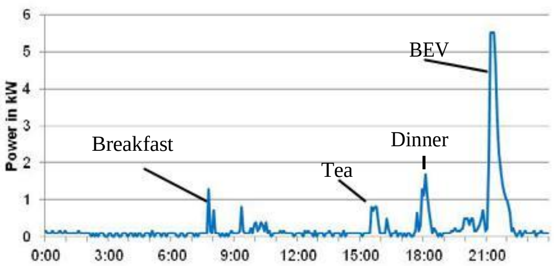

FIGURE 2: Electricity load curve of an exemplary household with an EV charged at 9 p. m.

Figure 2 shows the increase of peak demand of a household with an EV arriving at 9 p. m. It is obvious, that a charging at 20 kW would even worsen the situation. For this challenge two answers are given in the following.

4 Demand Side Management

From an electro-technical perspective the shortage in the distribution grid can be solved by an extension of the capacity in replacing transformers, (underground) cables, and other technical components. However, the costs are significant [12], the time horizons long and the acceptance of the construction work unclear.

Recently, another discussed solution is focusing on the new technology smart grids allowing communication between customers and electricity suppliers and, hence, a reversing of a main paradigm in energy economics: so far mainly the supply side had been controlled according to the demand (top-down paradigm). Now, smart grid technology allows influencing the demand side according to the (renewable) supply (bottom-up paradigm). Based on [13], [14] and [15] we define DSM as all measures that aim at influencing the electricity demand from the utility perspective, but require customer involvement and responsiveness to some degree (cp. Figure 3). Within DSM we have programs that aim at reducing electricity consumption (Energy Response (ER) Programs) and at changing consumption patterns, e. g. shifting demand from peak to off-peak periods (Demand Response (DR) Programs).

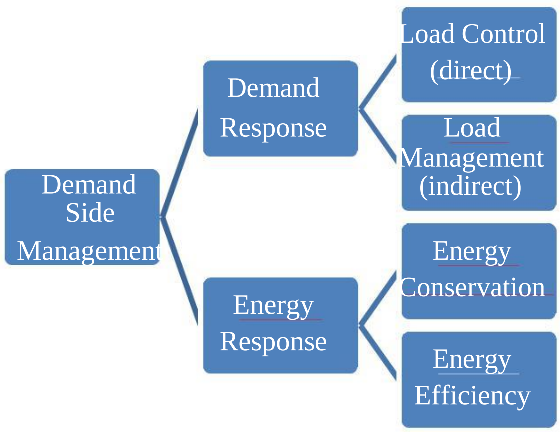

FIGURE 3: Definition of DSM measures

In recent years a lot of research has been done on dynamic pricing as one option of DR (Load Management). Dynamic pricing has mainly been tested together with smart metering and feedback devices in several field trials with residential households. While their energy saving effects – due to an observed rebound effect – are controversially discussed (cp. [16]), the current literature is focusing on their load-shifting effects

in households. Results from the GridWise Testbed Demonstration in Washington and Oregon indicate this effect, as consumers on a dynamic pricing scheme saved up to 30 % in comparison to the control group [17] in reducing their general electricity consumption and shifting their load from peak to off-peak times. A survey of demand response programs in the United States [18] shows that the load-shifting phenomenon dominates the energy conservation effect: peak reductions are partly overcompensated by an electricity demand increase in off-peak hours (valley filling). The German MeRegio field test with 1,000 households confirms this result: customers shifted up to 17 % of their electricity consumption but reduced their overall electricity demand only by up to three per cent [19].
Obviously, load-shifting effects also depend on the pricing mechanism, the tariff scheme and price differences. Furthermore, the day of time seems to be a significant parameter [19]. A recent review of 100 pilot programs [20] compares the effectiveness of different types of electricity tariffs for load-shifting: Time-of-Use tariffs (TOU: electricity price varies throughout the day, e.g. hourly) are less effective in shifting loads than Critical Peak Pricing schemes (CPP: extends TOU by allowing a further price increase if an unexpected shortage of electricity supply occurs).
EVs increase the load-shifting potentials of households substantially: the electricity consumption of the household nearly doubles and average parking times of about 23 hours a day seem to allow considerable flexibility in load shifting [21]. However, no consumer research has been conducted to our knowledge on the load-shifting effects of dynamic pricing on the charging behaviour of EVs. Nevertheless, DSM approaches such as dynamic tariffs together with smart meters and automatic charging signals seem to be an attractive and efficient solution to release the low voltage grid in the evening hours by postponing the charging process of EVs – its technical potential is depicted in the following.

5 An techno-economic perspective of controlled charging of EV

The maximum potential load within a neighbourhood differs strongly due to the different architectures of low voltage grids. Their analysis is always case specific and depends on the local specifications of the grid as cable length, type of cable, transformers, household types, number of EVs, location of EVs, charging time and power of EVs, etc. Therefore, we focus first on a higher aggregation level, the impact in an exemplary regional urban high voltage grid on 110 kV level and an EV-PV combination.
As depicted above, with uncontrolled charging most EVs would charge in the evening hours at home, where electricity consumption is already high and electricity generation with PV is low [22], [23]. Hence, domestic PV does not help to overcome this peak increase during the evening hours. Similarly, other renewable energy technologies, like biogas or hydro power, are inconvenient as they usually provide time independent base load (cf. Figure 4). Only wind energy might help to overcome this challenge – but only on seldom windy evenings. Therefore and for the sake of a higher share of renewable energy for EV charging, we argue again for a controlled charging of EV.

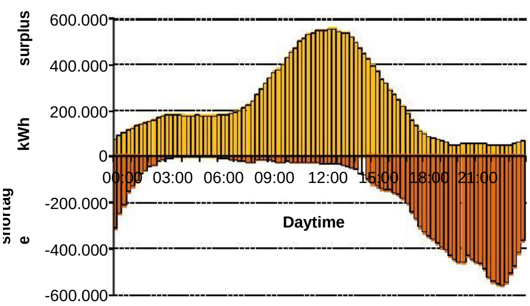

FIGURE 4: Shortage and surplus of EV charging based on RES-feed-in. Sum of all hours in a year each quarter hour column; charging after last daytrip. Data sources: [22], [23]

To allow a more profound analysis of this situation we developed a regional electricity system model with renewable energy generation capacities, a high voltage grid, and the demand side. The model comprises all city districts which are supplied by transformer stations (TS) as nodes of the high voltage (110 kV) grid. The lower distribution grid is not modelled. Therefore, the local load is concentrated at the TS. A model run consists of a full year with hourly time steps. The concept of the model can be found in [24] and in more detail with selected results in [25].
The charging load of the EV is estimated on the MiD 2008 database, a representative study of ICE cars and mobility in Germany [26]. For the following analysis we assume a maximum EV penetration – i. e. 95 % of all cars are BEV. Exemplary German load curves for winter,

summer and transition days with uncontrolled direct charging at the household socket with up to 3.5 kW in the city district are displayed in Figure 5.

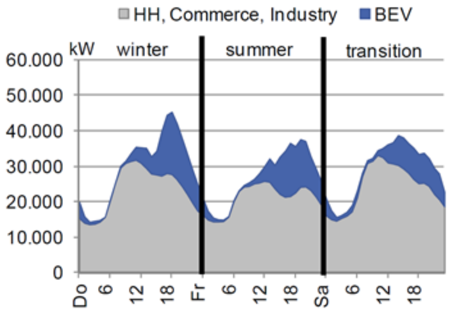

FIGURE 5: Load curve of a city district with uncontrolled charging (3.5 kW) and 95 % BEV penetration

Unsurprisingly, the BEV charging increases the peak loads especially in the early evening on working days. In order to cut these increasing load peaks we included dynamic electricity prices into the model and optimized the charging load with the aim to minimize the system costs for electricity provision.

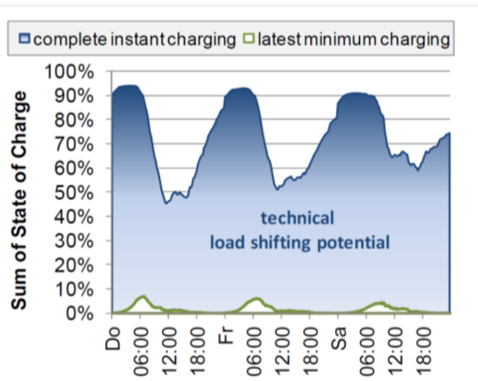

FIGURE 6: Technical load shifting potential of the EV fleet; own calculations based on [24]

For the controlled charging, not each of the 130,000 cars in this city is modelled but the sum of all BEVs of each city district. To determine the load shifting potentials of the BEV we determined the highest possible state of charge (SoC) of the battery for all cars (charge whenever they can) and the lowest possible SoC (charge as late as possible and only as much to accomplish the next round trip) (cf. Figure 6). The area between these two curves is the load shifting potential: all charging strategies allow the vehicle user to accomplish all trips and the electricity provider can optimize the load within these boundaries.

Introducing a real-time pricing scheme based on the electricity prices on the German spot market and assuming complete rational and expense minimizing users (*homines oeconomici*) the impact on the charging behaviour is considerable. In this idealized situation new load peaks during off peak times can be observed (cf. Figure 7) caused by low electricity prices in these hours. Even though, in reality this effect is rather unlikely.

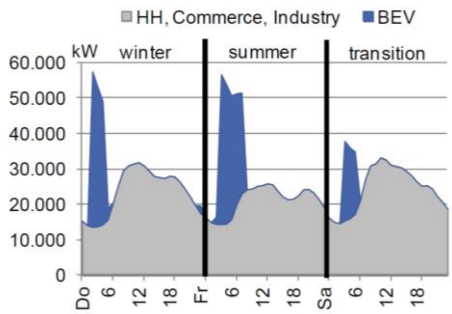

FIGURE 7: Controlled charging with a dynamic tariff based on the spot market prices

An additional effective measure would be to reduce the maximum charging power by half (to 1.75 kW) . Furthermore, the dynamic tariff above is modified by taking into account a high share of local electricity generation by renewable energies, i.e. lowering the price in times of high electricity generation by PV and wind.

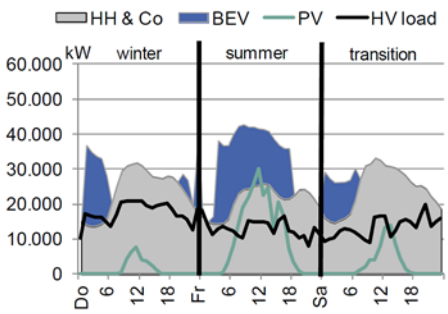

FIGURE 8: Controlled charging with restricted power and an extended dynamic tariff

This reduction of maximum charging power together with a more appropriate dynamic tariff (not displayed in Figure 8) leads to lower peaks in the load curve in the city district (cf. Figure 8). The more balanced load on high voltage lines does not directly correspond with one (displayed) city district, but is due to the total load and grid topology in the city.

On the lower voltage levels these interrelations are even more critical (cf. [27]) . Whereas, on national level (transmission grid) the interrelations are smaller but, the influence to the grid and the generation mix is still significant (cf. [28]). An optimistic fleet of 12 million EV in Germany (30 % market share) until 2030 and uncontrolled charging would lead to an increase of peak load by 12 % and a higher CO_2 certificate price. Through controlled charging the peak load increase is significantly lower and about 600 GWh wind power have not to be throttled due to feed-in management. Simultaneously, the controlled charging rises the electricity generation by hard coal rather than by the 'cleaner' but more expensive gas turbines [28]. This might unfortunately lead to nearly unchanged specific CO_2 emissions per kWh in the grid.

6 Acceptance of controlled charging of EVs

As pointed out in Chapter 4 several DSM approaches have been tested regarding household appliances, however no results are reported on the acceptance of these approaches for EVs so far. Therefore, a field trial with 34 BEVs (Smart electric drive) was conducted in the German cities of Stuttgart and Karlsruhe over a period of nine months in 2011. By conducting telephone interviews during the field trial, the acceptance of controlled charging was analysed. The controlled charging mechanism was implemented as follows: The electricity price for vehicle charging was structured as a TOU tariff with two price levels. A further discount was given, if customers reported (via a smartphone application) to the utility for how long they were plugged at a charging station. During this time frame the utility was able to control the charging procedure (by delaying the charging process), but had to guarantee a fully charged battery by the end of the time frame defined by the customer.

The results of this field trial (cp. [29]) show that users usually plugged in their Smart ed during evening hours and made full use of the TOU tariff. However, this was not necessarily motivated by the cost-saving potential, but was mainly the time when the customers arrived home after work. Only a minority reported to check electricity prices first and plug-in the car accordingly. Furthermore, environmental benefits played a major role in doing so, as low-priced zones were associated with a high share of renewable supply. In contrast to household appliances the use of "green" electricity for the EV was rated as more important, because of the guaranteed emission-free driving. This was one key issue for applying for the EVs in the first place. Interestingly all participants had reported their willingness to adapt the charging process according to electricity prices if it starts automatically. This is somewhat surprisingly because the possible cost savings are very small – especially in comparison to the high vehicle price. Consequently, all participants asked for smart charging stations which automatically start the charging process during off-peak hours. However, a few participants had concerns about automated solutions regarding the battery lifetime. This was also an issue when thinking about V2G solutions. However, those participants that owned a PV systems at home, showed high interest in V2G options in order to maximize their internal consumption.

7 Conclusions

Concluding, the paper gives an overview of the future German electricity market with the focus on EV integration. It is shown that the impact on the regional (and local) power grid and the electricity system is remarkable, even though the influences in the transmission grid and in generation are low for reliable EV penetration rates.

DSM can help to reduce the impact on the grid in postponing the charging process and shifting load from peak to off-peak hours. From a socio-economic perspective the acceptance of users is positive if the postponing process is automated and assures a higher share of renewable generated electricity. From a techno-economical perspective we confirmed a high load shifting potential in an optimising model of an exemplary regional electricity system on the high voltage level. We conclude that DSM (i.e. dynamic tariffs) in combination with smart grids is highly suitable to tackle the increased peak-loads and to increase the share of renewable electricity generation feed-in by automated controlled unidirectional charging. However, we overestimate the potential due to the underlying assumption of *homines oeonomici* and high EV shares. But we can state that EVs increase the existing load shifting potential from private households considerably.

DSM measures seem to be necessary to assure an affordable and efficient future energy system. Dynamic tariffs seem to be a suitable candidate to resolve most of the challenges of integrating EVs in the electricity grid. Further research on the acceptance is still needed.

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